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TURBULENCE FORECASTING

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In order to forecast turbulence, one needs to have an understanding of the cause of turbulence. Therefore, we shall attempt to show the atmospheric structure that often results when aircraft encounter moderate or greater turbulence. The following is based on thousands of hours of observations of flights over the past 39 years of aviation meteorology.

1. AIRMASS ANALYSIS

One of the best tools in analysis and forecasting turbulence is the frontal contour method of airmass analysis as perfected by the Canadians in the late 1940's and early 1950's.

In winter, on the average, one will find four major frontal zones (five airmasses) between about 20N and 50N latitude over the eastern United States. Figure 1 shows the mean position of the various surface fronts during an average winter. Large day-to-day variations often occur as well as mean year-to-year positions during the colder months. In summer, the Sub-Tropical surface front average position is just south of the Great Lakes and the upper air position is over the lakes. As before, there are large day-to-day variations in these positions. Figure 2 shows the same frontal positions but within the upper troposphere. Average temperatures are also shown at other MB (millibar) heights as well as mean heights/temperatures of the airmass tropopause.

We shall now look at vertical cross sections of the various frontal models and often associated wind maximums in winter. Figure 3 shows a typical model of the Arctic front with a wind maximum at about FL230* or near the 400 MB level. Southward, we find the Maritime Arctic frontal zone (often called Sub-Arctic) with a wind maximum much stronger at about FL290-300 or near 300 MB. This is shown in Figure 4. The next southward frontal zone is the polar front as shown in Figure 5. We see an average wind maximum of about the same strength as the Maritime Arctic but a maximum wind level of near FL340-350 near 250 MB. The most southern frontal zone (except in rare cases) we call the Sub-Tropical frontal zone. The height of this maximum moves up to near FL390 at 200 MB. This frontal model is shown in Figure 6.

At the higher levels above about 400 MB, we occasionally see a frontal zone south of the Sub-Tropical front in the temperature range of near -34° to -35° C at the 300 MB level. It appears now and then in the tropical areas in winter and even over the United States during the warmer months. Likewise, we occasionally see frontal zones north of the Arctic front in very cold airmasses and we call this frontal zone the Super Arctic.

*FL230 = Flight level of 23,000 feet above mean sea level.

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2. FRONTAL TURBULENCE

All of the frontal zones shown on Figures 1 through 6 may contain turbulence to some degree. Above about 12,000 ft, most of the turbulence will be of the clear-air type (CAT) due to descending air within the frontal zones. Figure 7 shows all four of the major frontal zones and the area of frequent, moderate, or greater CAT. As the altitude increases toward the "Z layer" (level of non-horizontal temperature gradient), the CAT will decrease reaching a minimum at the Z layer. This altitude of the reversal of the thermal wind, located at the level of maximum wind speed, is a desired level to fly for smooth air (jet core). One has only horizontal wind shear rather than vertical and horizontal shear. The altitude for maximum turbulence seems to at about two-thirds of the way from the surface front to the Z layer for each frontal model as shown in Figure 7. The colder the airmass, the lower the CAT zones within each frontal model. This is the reason that CAT is found at the lower altitudes in winter. Likewise, the lower latitudes result in the height of the CAT being found at higher altitudes within the frontal zones.

3. TROPOPAUSE TURBULENCE

Tropopause surfaces below about FL310 very seldom contain moderate or greater CAT. Cold airmasses north of the Maritime Arctic frontal zone result in sinking air. The resultant low tropopause does not contain enough of a temperature inversion and associated horizontal and vertical wind shear. Tropopause surfaces at and above about FL340 (250 MB) are the ones that often result in moderate or greater CAT within the ascending airmasses. Most CAT within tropopause surfaces will be found in temperatures colder than standard as well as temperature inversions, horizontal and vertical wind shear. Figure 8 shows various vertical temperature signatures through tropopause surfaces. Curves A and B seldom result in more than light CAT. Curves C and D often result in moderate or greater CAT at temperatures colder than standard if relative high wind speeds are present.

Figure 9 shows B, C, and D temperature curves across a typical frontal model and associated jetstream.

4. MOUNTAIN WAVES

The mountain wave is highly over-rated as a direct cause of clear-air turbulence. In fact, Delta Air Lines has been flying to the west coast for over 20 years from various cities east of the Rockies. We do not know of one case in which a Delta aircraft has encountered moderate or greater turbulence caused solely by a mountain wave when flying at altitudes above 25,000 feet. We have encountered turbulence many times over the mountains but the cause was determined to be upper front, tropopause, trough, or ridge lines when it was the CAT type. In some cases, the discontinuity was located within a wave condition and the turbulence within discontinuities may well be enhanced by mountain waves.

Figure 10 shows a mountain wave model with two frontal zones (three airmasses). As long as flights avoid the upper front and tropopause surfaces, flights are most always very smooth. In some cases, aircraft within the wave crest may well exceed the aircraft airframe speed limitations. In some of these cases, aerodynamic buffet may occur which no doubt results in often reported turbulence. Figure 11 shows that eastbound aircraft are more apt to experience this overspeed buffet due to the very sudden encounter due to high ground speeds. The example shows a 13-second difference between downwind versus upwind, which gives the headwind flight crews a much longer period in which to react to the ascending air.

5. CLOUD TURBULENCE

In this analysis, we will exempt all types of convective clouds except a few special cases of thunderstorms associated with widespread cirrus. As a general rule, cirrus results in only light turbulence in areas of relative light winds. Under moderate to strong winds, there is often found moderate turbulence near the cirrus tops and in this area there is a strong increase in wind speed near the cloud top. Most of the turbulence will be found within the last 1000 feet just before the top. This condition is shown in Figure 12. The cloud retards the horizontal wind flow (cloud drag) and as the top is approached, there is a sharp increase in wind speed as well as turbulence.

There is one condition that aircraft flying a higher levels encounter several times a year that result in passenger injuries. This is also shown in Figure 12 where the aircraft is flying on top in the clear. Below the cirrus, a thunderstorm has formed and the top has merged into the higher cirrus deck. The major updraft of the thunderstorm has created a bubble or ridge-row near the top of the cirrus deck. Flight crews often do not see this ridge-row or bubble and will just nick the top or pass through the wave effect just on top. In most cases, there is one sharp shock that results in a messy aircraft and/or injuries if seatbelts are not secured. To avoid this, weather radar tilt control tilted downward for the target should be used and then go either right or left of the target rather than the risk of flying the wave effect just on top.

6. TROUGHS AND RIDGES

Most always there will be some type of turbulence within trough lines. In most cases, it will be of short duration at any altitude and is more apt to be only light to moderate. Sloping trough lines seem to enhance the turbulence. Figures 13 and 14 show both a ridge line and trough line as it may appear on an upper air chart. In many cases, ridge lines give airborne aircraft many more problems than trough lines as often associated upper warm fronts, widespread cloud cover, and sharp cold air tropopause surfaces above the warmer airmasses below.

7. LOW-LEVEL CYCLONIC FRONTAL WAVES

Moderate to severe low-level turbulence is often caused during the cooler months by shallow, warm frontal cyclonic waves that may appear anywhere, but the severe cases favor the east coast of the United States as shown in Figure 15. Strong northeast surface winds with strong southwest winds above are only a few miles north and north-northeast of the center of the wave. Figure 16 shows a vertical cross section along the line AB as shown in Figure 15.

8. EXAMPLES OF FLOW PATTERNS THAT OFTEN RESULT IN MODERATE/SEVERE TURBULENCE

Figure 17 shows a very sharp upper warm front within a ridge line that most always will result in moderate to severe turbulence. Near the crest of the ridge line within the frontal zone, the warm front will produce the worst upper air turbulence within the tropopause than any other feature. Likewise, above the jet core and to the south toward the high pressure side, the cold tropopause will contain moderate to severe CAT in many cases.

Figure 18 shows a cold cut-off cold low with an upper jet front. The area north through northeast of the closed low is the area of frequent, moderate, or great CAT as we have two frontal zones, sharp trough line as well as cold sloping tropopause surface above the frontal zones. It is very important to fly the Z layer under this flow pattern or well above the tropopause. The lower levels in some cases may well prove to be relatively smooth. Figure 19 is a vertical cross section along the line AB which shows the areas of turbulence.

Figure 20 shows the position of the surface front and associated upper air position. The Coriolis effect comes into play as the cause of this type of turbulence, which in most cases will be only light but found at most all altitudes above about 15,000 feet. Cross contour flow is present above and near the surface position of the front.

9. FORECASTING TURBULENCE AT DELTA AIR LINES

In order to forecast turbulence, one has to have the proper analysis on large scale actual surface and upper air charts. Delta's actual upper air chart for 0000-1200 GMT contains computer-plotted data from 400, 300, 250, and 200 MB plus the height and temperature of the tropopause as well as maximum wind data. All this information is plotted on one large-scale chart and then the analysis is done by a Delta meteorologist. The actual charts also contain wind and temperature information from aircraft that has INS and ACARS equipment. This is hand plotted at present. Short-range forecasts are then made with the help of the Bracknell computer forecast of winds and temperatures at 12, 18, 24, and 30 hours from base data which also is plotted by computer at the same levels as the actual charts. Frontal analysis may be made on the forecast charts as on the actual with the corrected position of upper fronts and maximum wind. Both Suitland and Bracknell computers forecast the position of the maximum wind in error by about 60 miles too far on the

high-pressure side in warm fronts in ridge lines. Both, also, underforecast the maximum wind speed by 30 to 40 knots in the case of Suitland and 15 to 25 knots in the case of Bracknell. The decrease in wind speed on the low-pressure side of the maximum is also in error by both Suitland and Bracknell but Bracknell will show a tighter gradient on the low-pressure side as it should be. Figure 21 shows the actual for 1200 GMT on March 31, 1986, for the Pacific Northwest with Maritime and polar fronts.

Figure 22 is a sample Delta turbulence alert that Delta's meteorologists enter into the Delta flight planning system by grid numbers, and if an aircraft passes through the area, it will be picked up by the Delta computer weather system and be placed on board the flight (B20). The second alert is for thunderstorms (T21).

For Delta's international flights, a more detailed flight forecast is made for turbulence by the Delta meteorologists as shown below:

> Delta 14/24 --- Lgt/Mdt CAT CLB FL 290-310 upper front --- Lgt CAT 40SW GVE FL330 trop temp rise --- Lgt CAT ACK trough FL350 --- Lgt/Mdt CAT FL370 50NE YYT trop temp drop --- Lgt 33W ridge line --- Lgt/Mdt CAT 30W CRK FL370 trop temp rise --- Lgt CAT DVR trough --- Lgt CAT descent FL290-280 trop --- Mdt CAT FL220-200 descent front.

Delta's meteorologists and flight dispatchers have access to company VHF for most of the route structure as well as HF for the international flights.

QUESTION: George Modica (AFGL). Do you have a large concern for tropopause folding type turbulence? And if so, what meteorological information do you look for?

ANSWER: We don't believe such turbulence really exists. In our practice at the Z layer, the "trop" is above it and the front is below it. If you want to extend that tropopause down into the top of the upper front, and you can do so, there is a lot of shear there. But if you go through at the Z layer horizontal, we hardly ever find any significant turbulence.

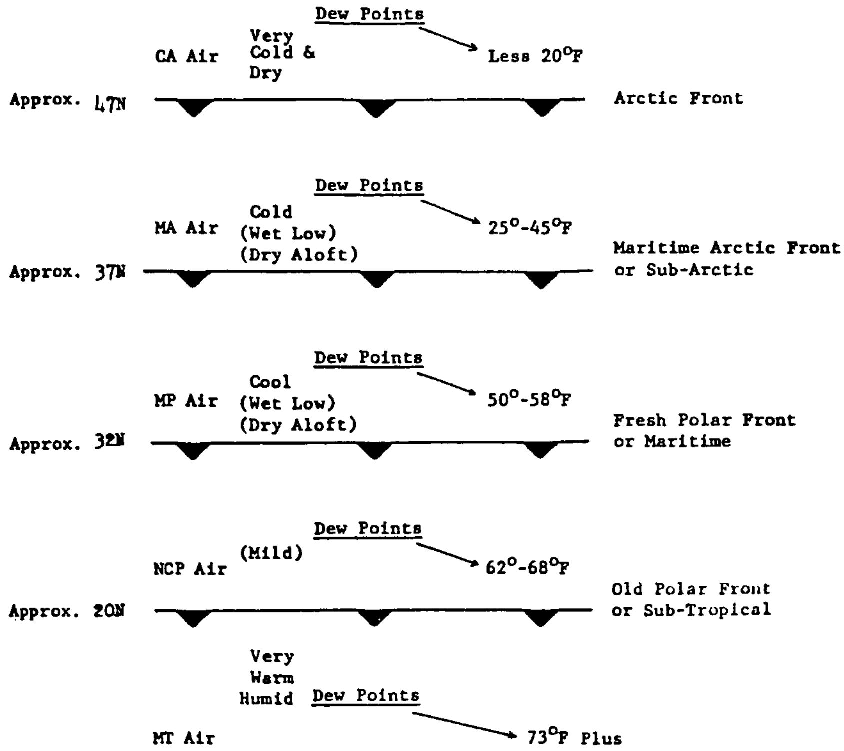


Figure 1. The mean position of the various surface fronts in the eastern United States during an average winter.

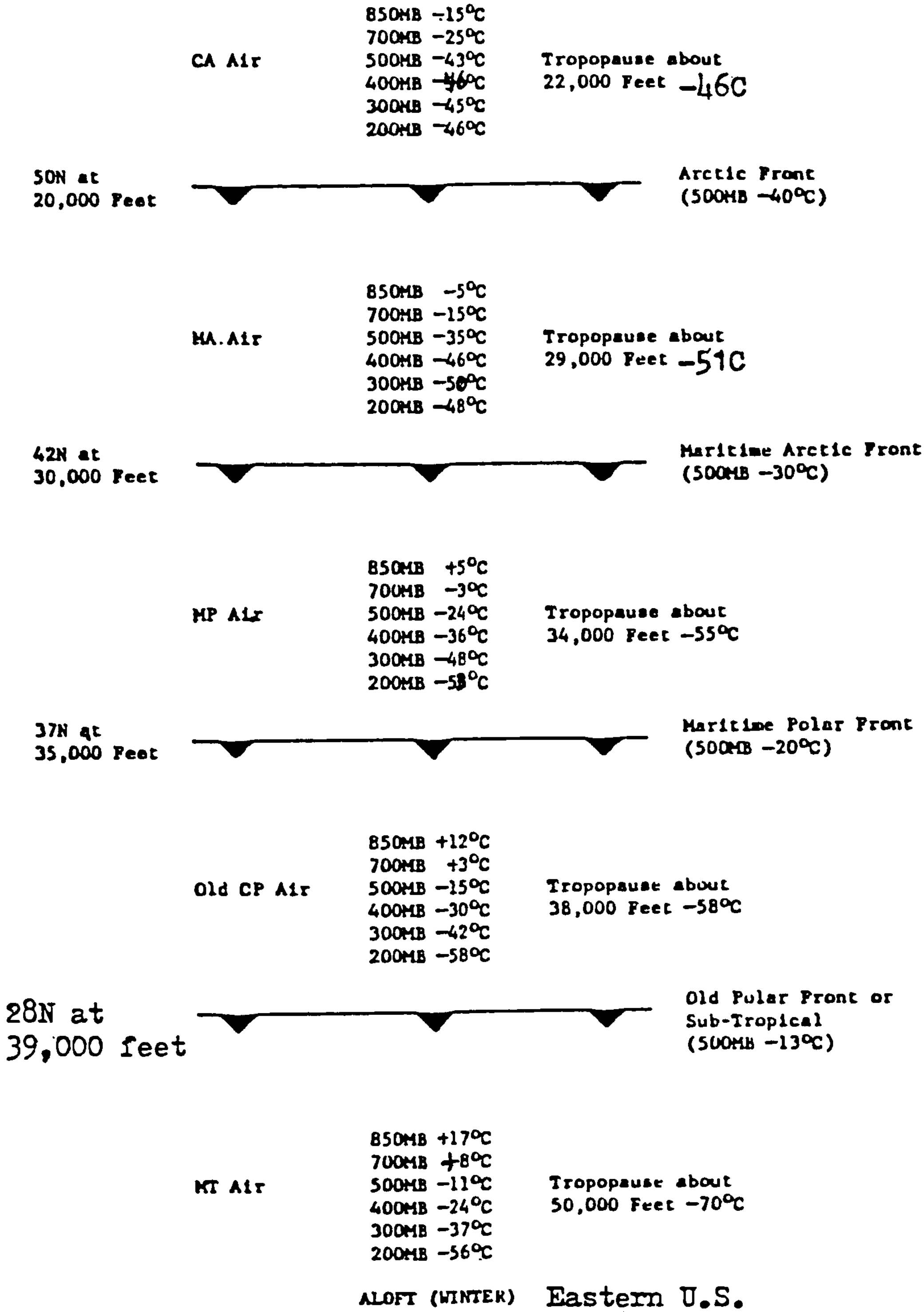


Figure 2. The mean position of the upper troposphere in the eastern United States during an average winter.

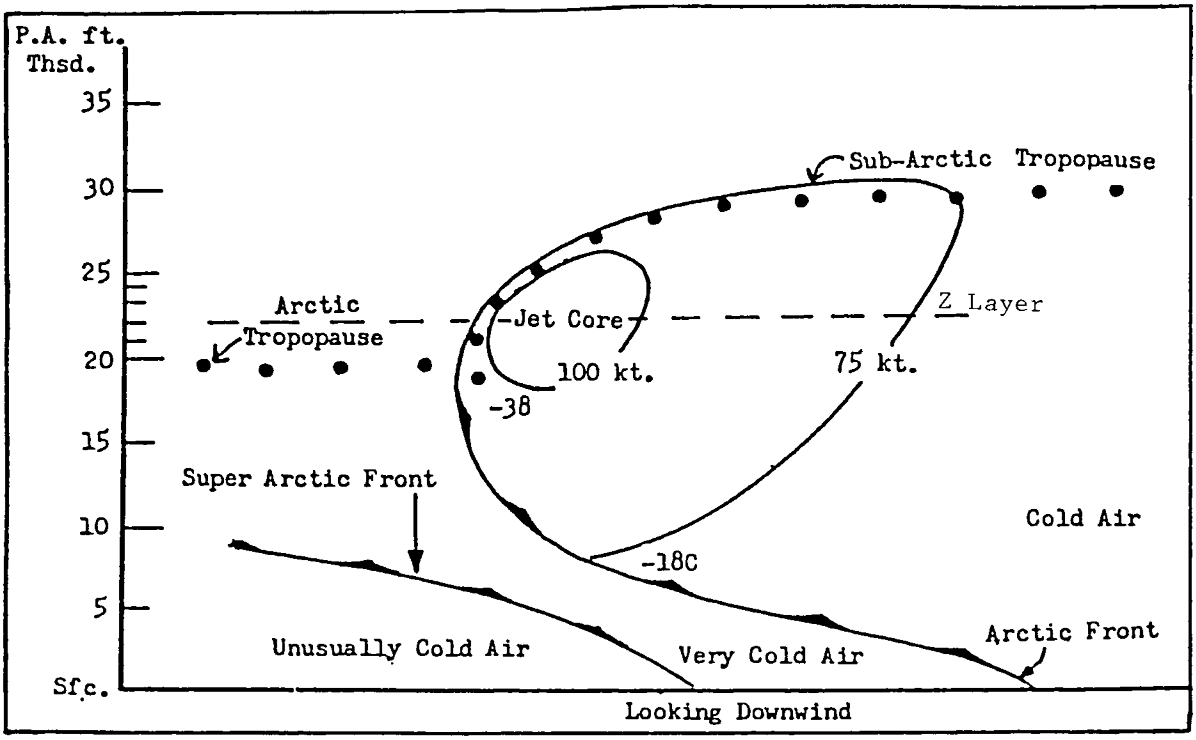


Figure 3. A typical model of the Arctic front with a wind maximum at about FL 230 or near the 400 MB level.

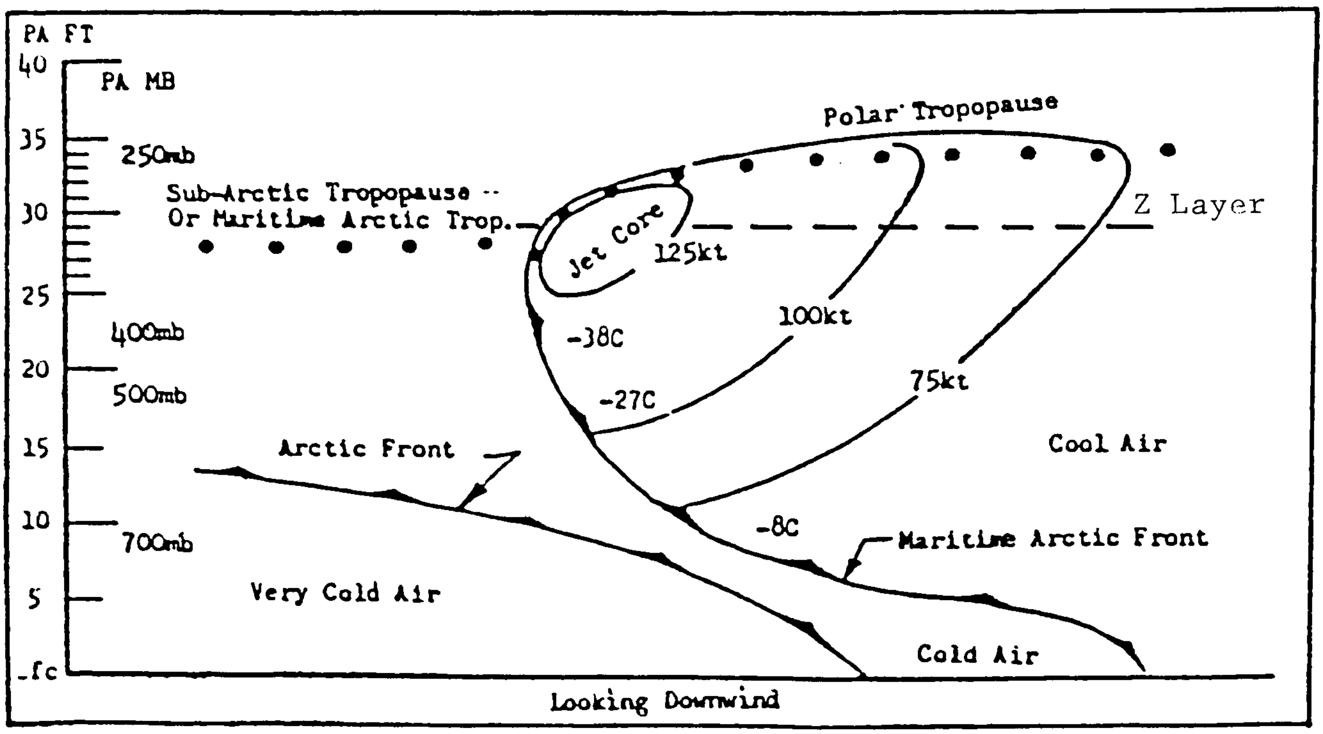


Figure 4. A typical model of the maritime Arctic frontal zone with a wind maximum at about FL290-300 or near 300 MB.

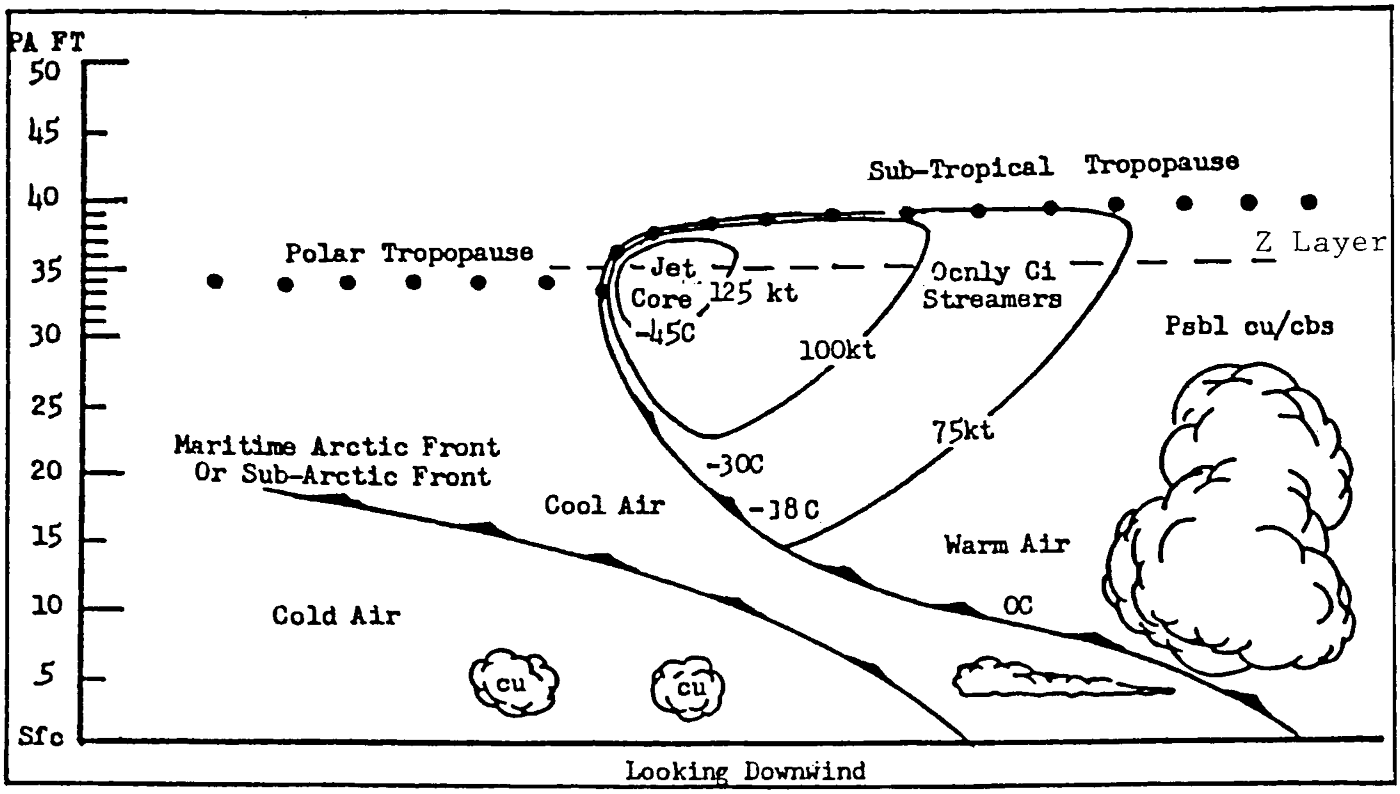


Figure 5. A typical model of the polar front with a maximum wind level of near FL340-350 at 250 MB.

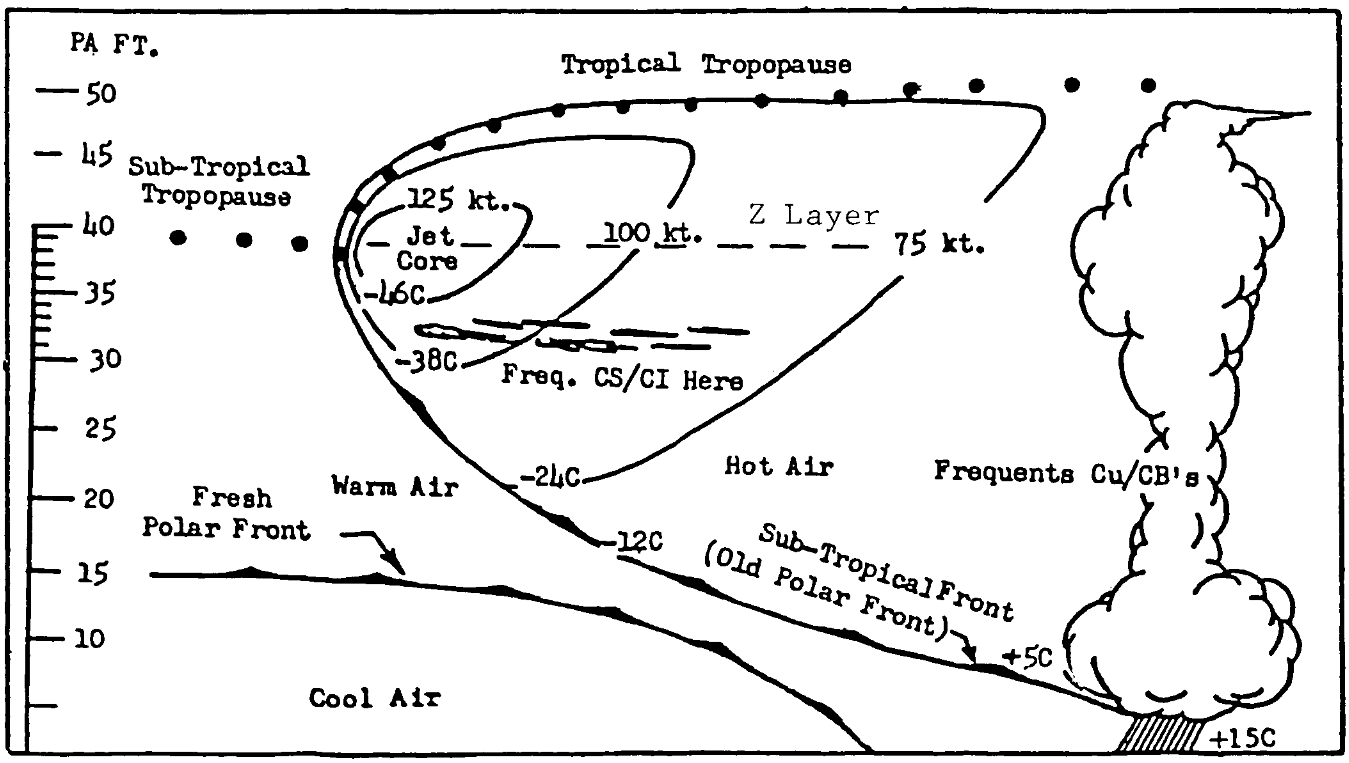


Figure 6. A typical model of the sub-tropical frontal zone with a wind maximum at about FL 390 at 200 MB.

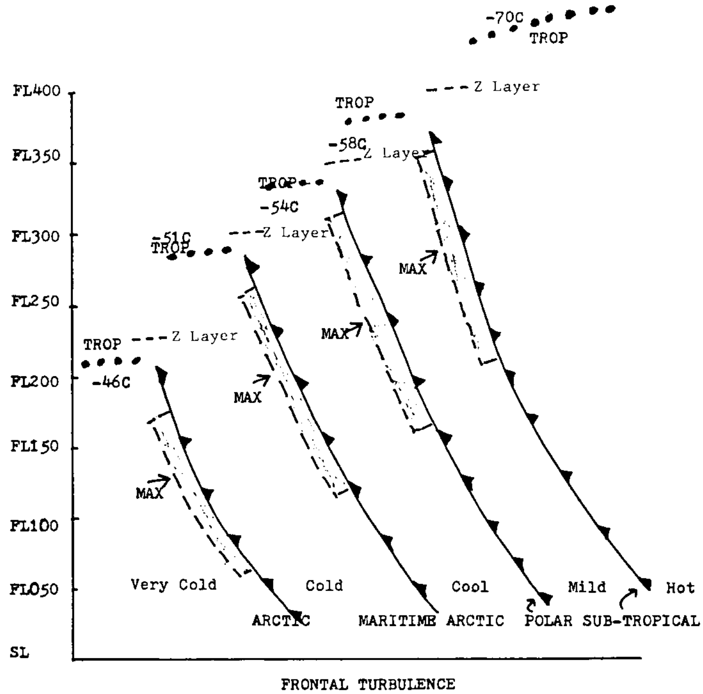


Figure 7. All four of the major frontal zones and the area of frequent, moderate, or great CAT.

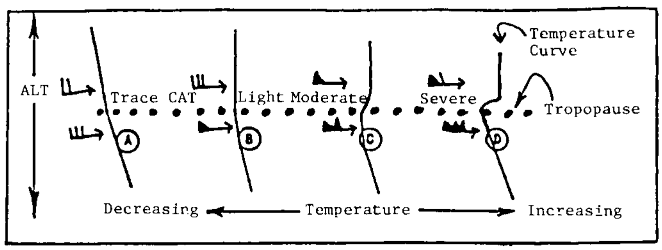


Figure 8. Various vertical temperature signatures through tropopause surfaces.

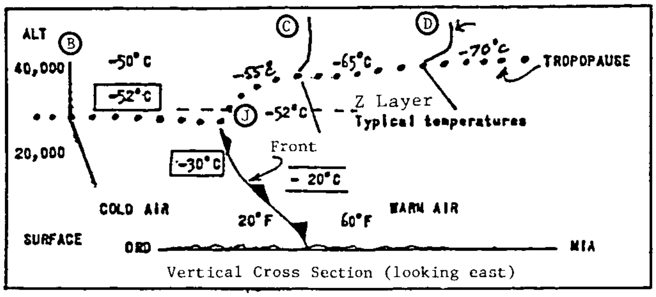


Figure 9. The B, C, and D temperature curves across a typical frontal model and associated jetstream.

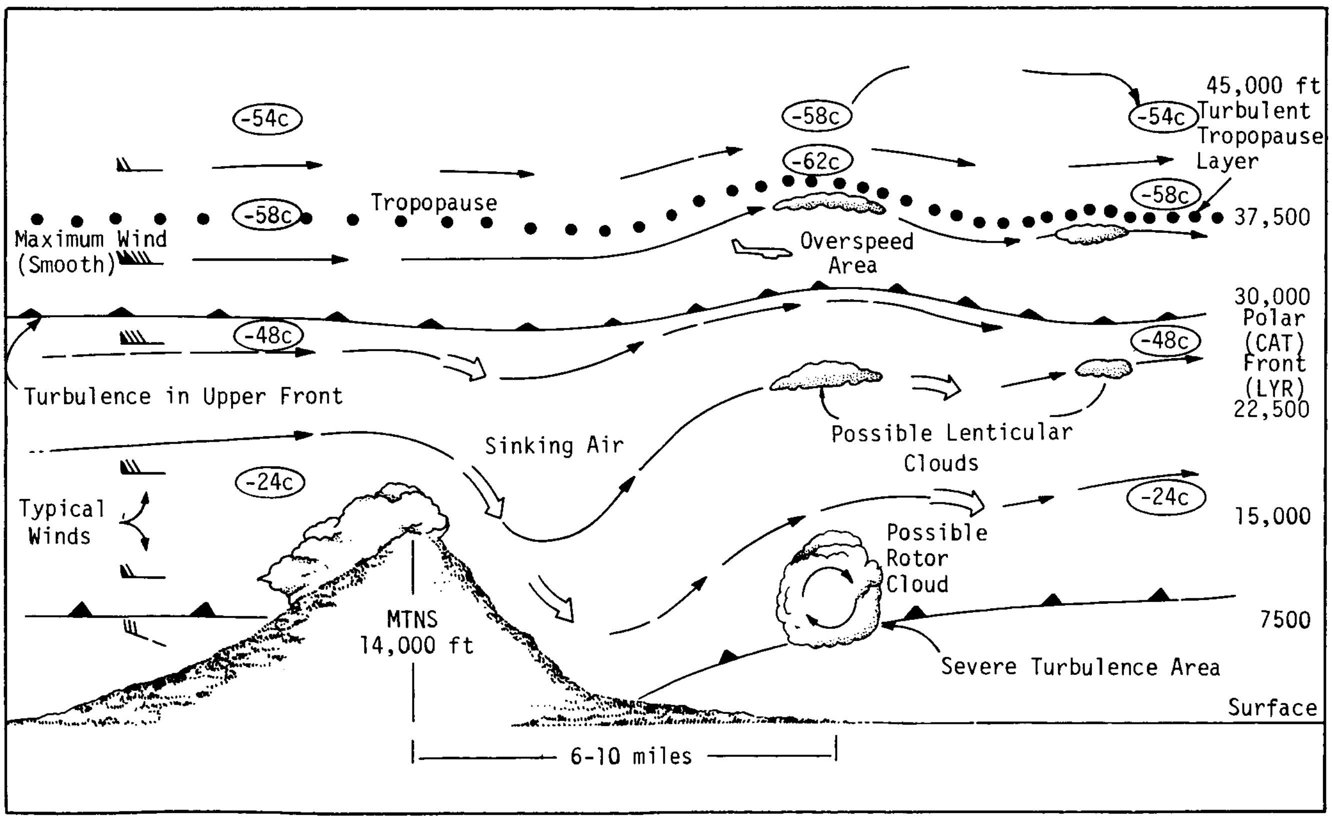


Figure 10. A classical model of a mountain wave.

Westbound GS 377 knots - Time in updraft 38.5 secs.

Eastbound GS 577 knots - Time in updraft 25.2 secs.

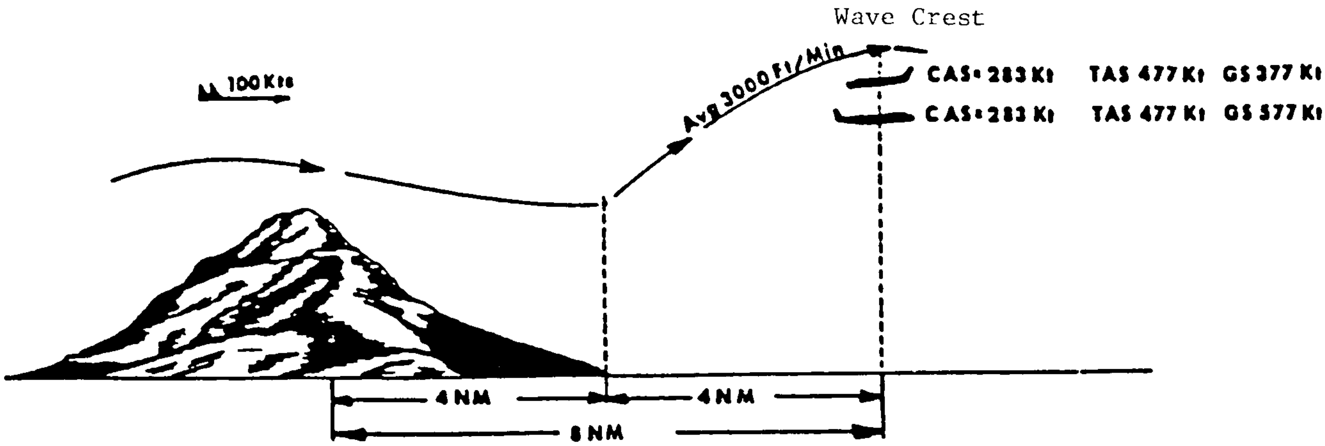


Figure 11. A typical wave with updraft.

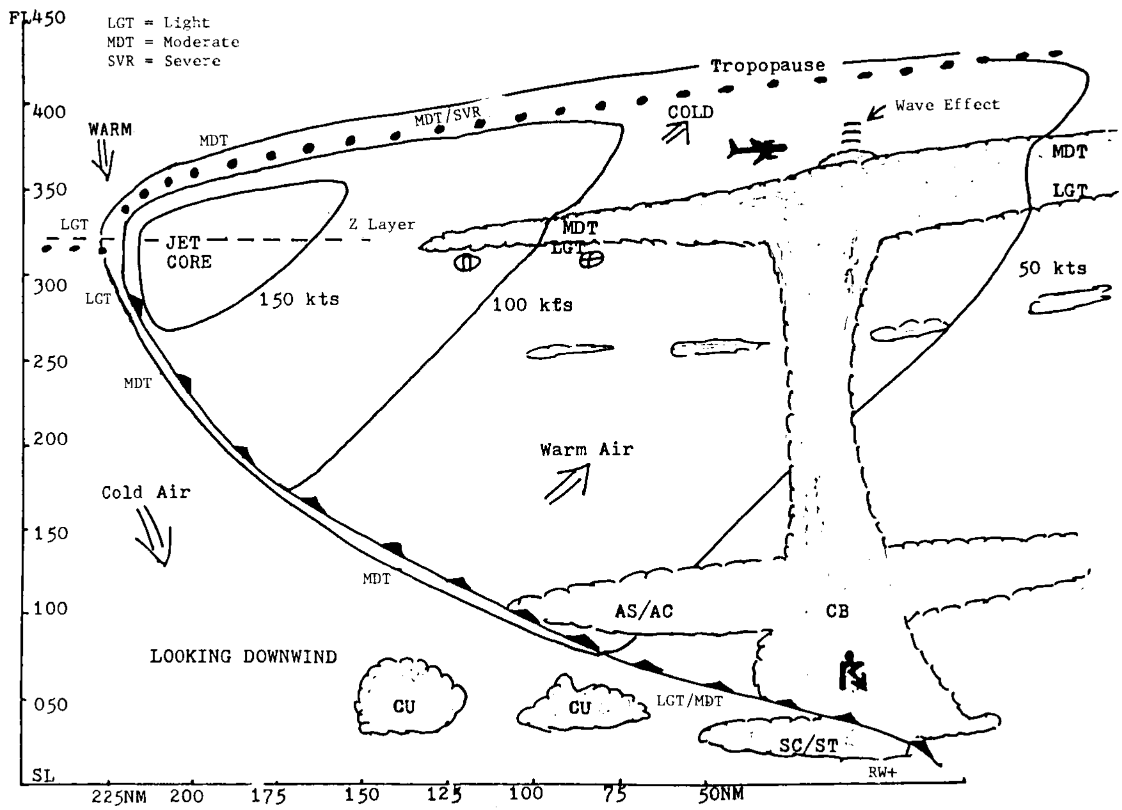


Figure 12. Cloud turbulence.

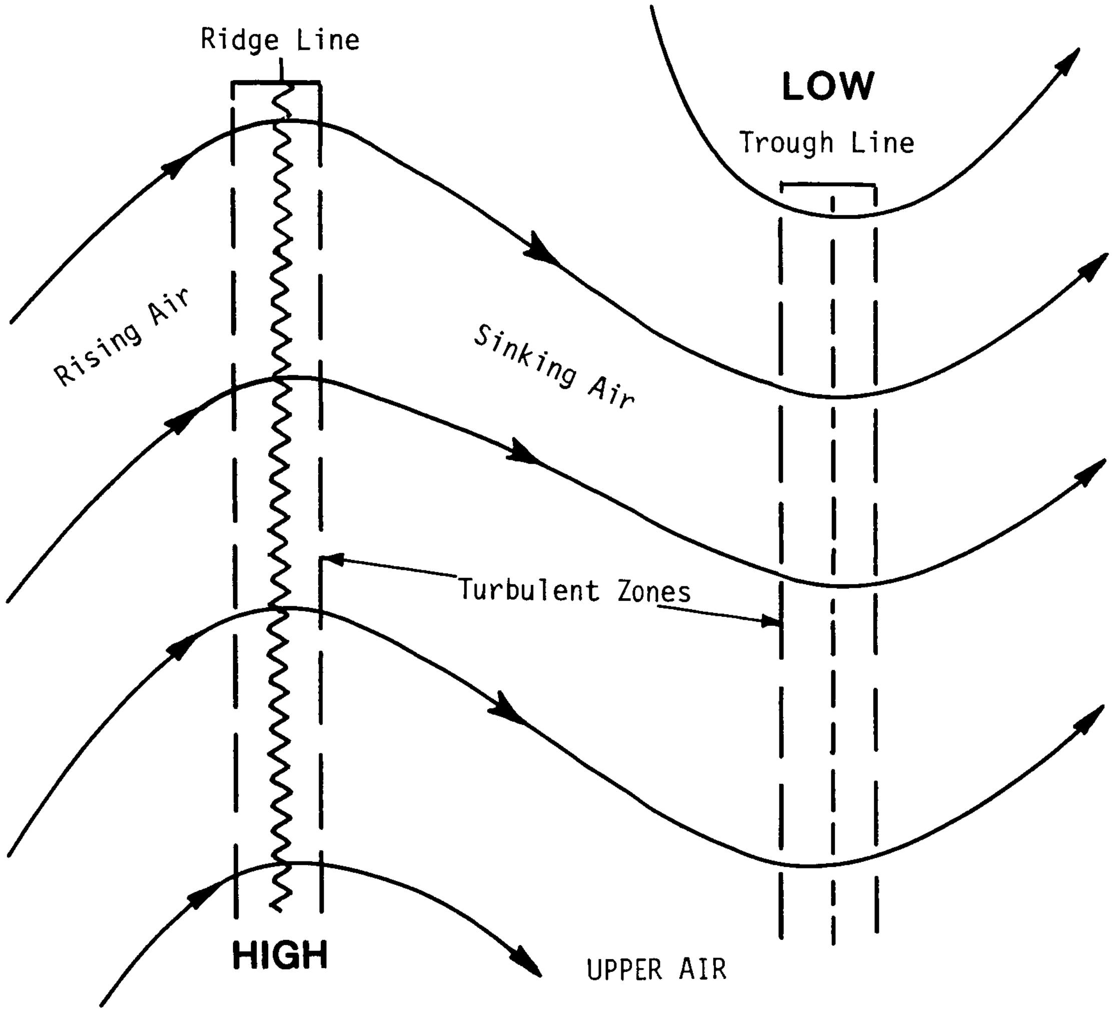


Figure 13. A ridge line as it may appear on an upper air chart.

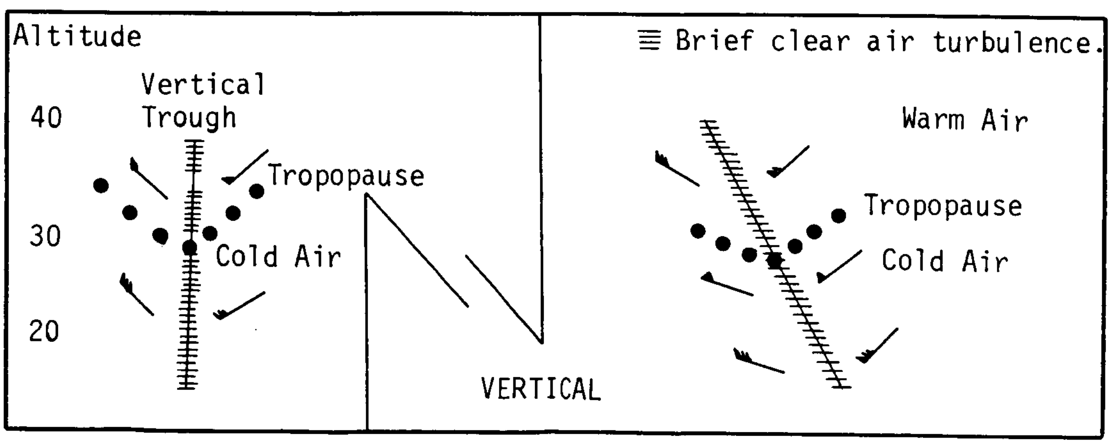


Figure 14. A trough line as it may appear on an upper air chart.

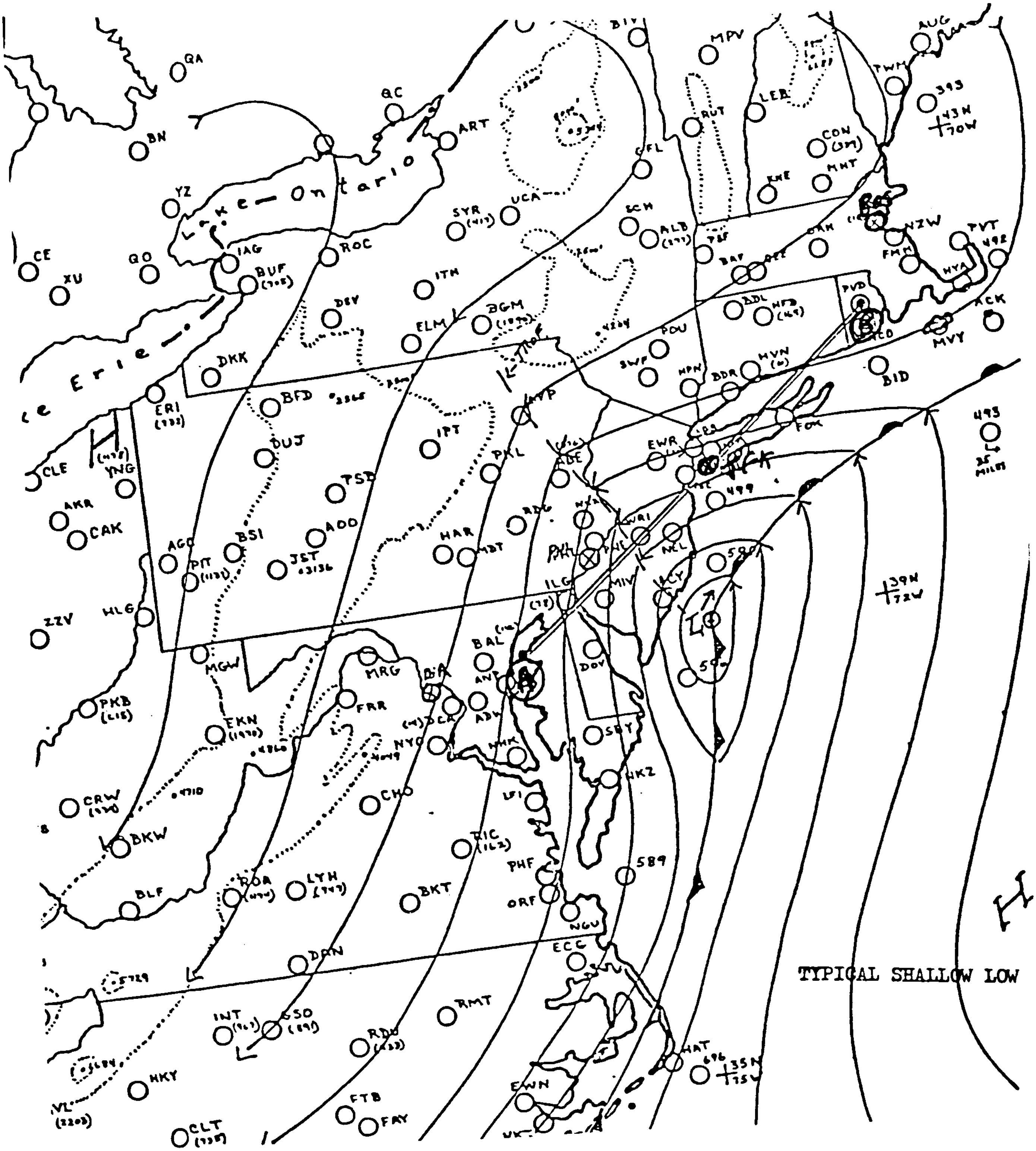
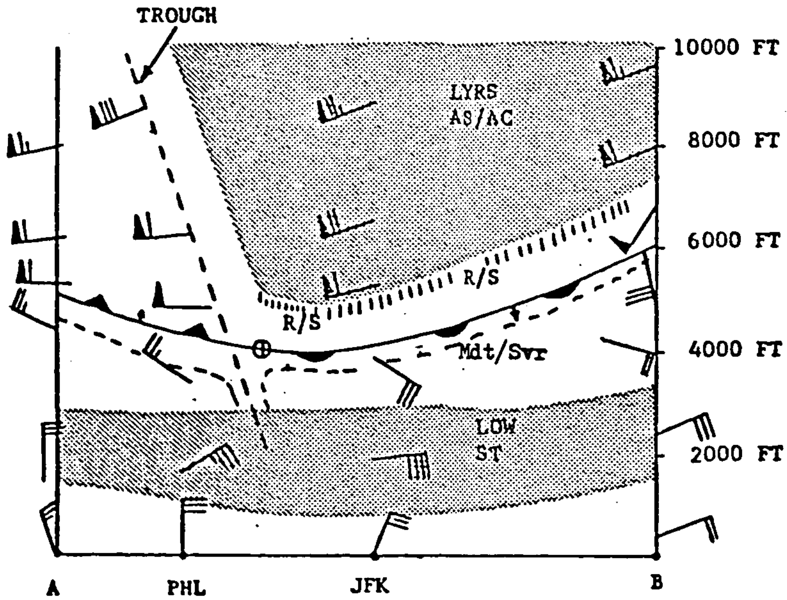


Figure 15. Severe cases of moderate to severe low-level turbulence in the east coast area of the United States.



Most of the turbulence would be found along the frontal zones (about 4000 ft at JFK and 6000 ft at B). Also, along the sloping trough line.

Figure 16. Vertical cross section along the line AB.

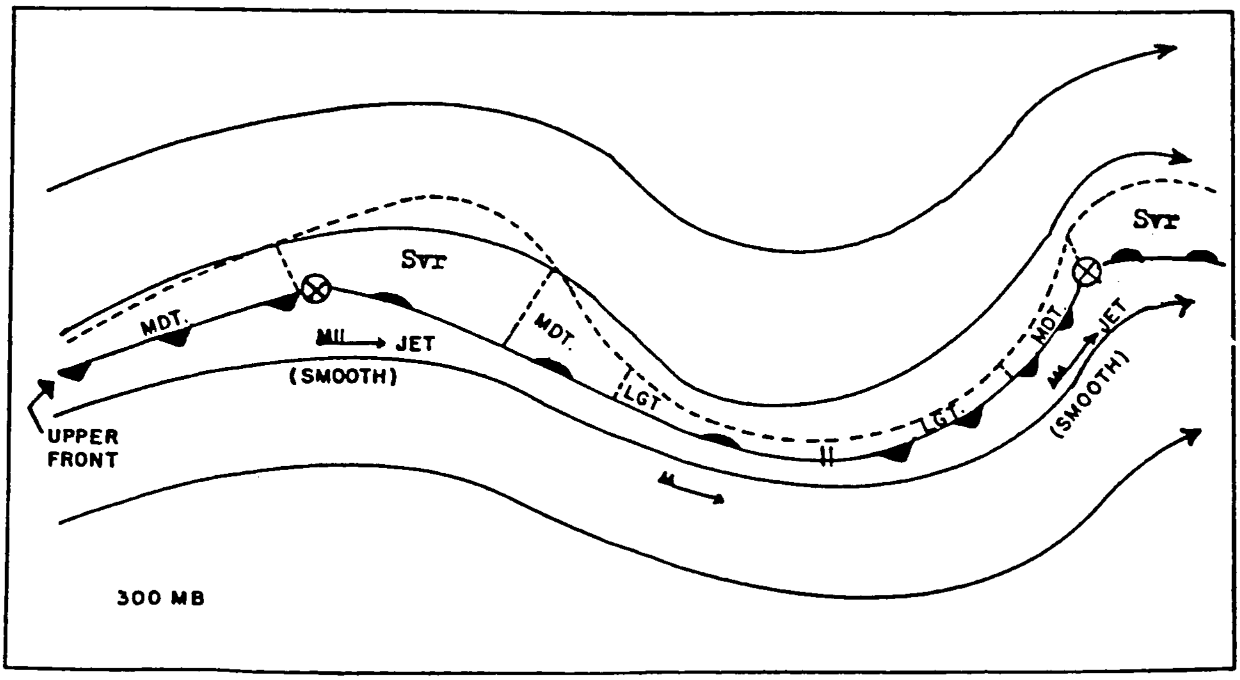


Figure 17. An illustration of a very sharp upper warm front within a ridge line that most always result in moderate to severe turbulence.

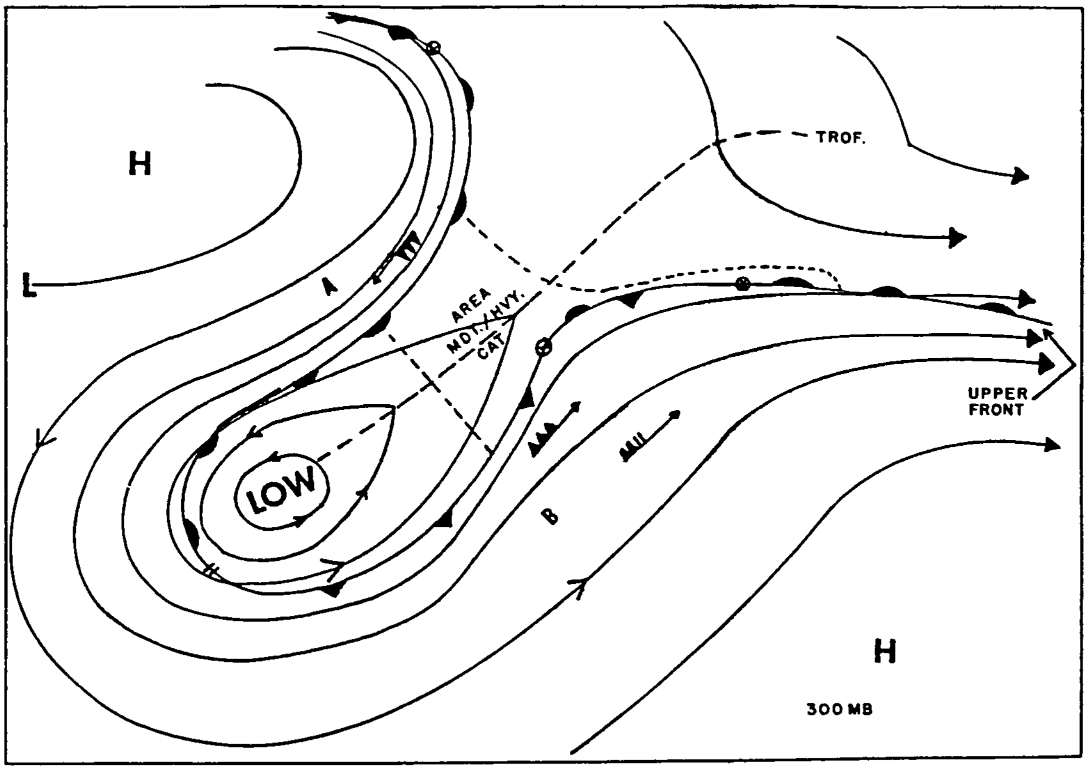


Figure 18. A cold cut-off cold low with an upper jet front.

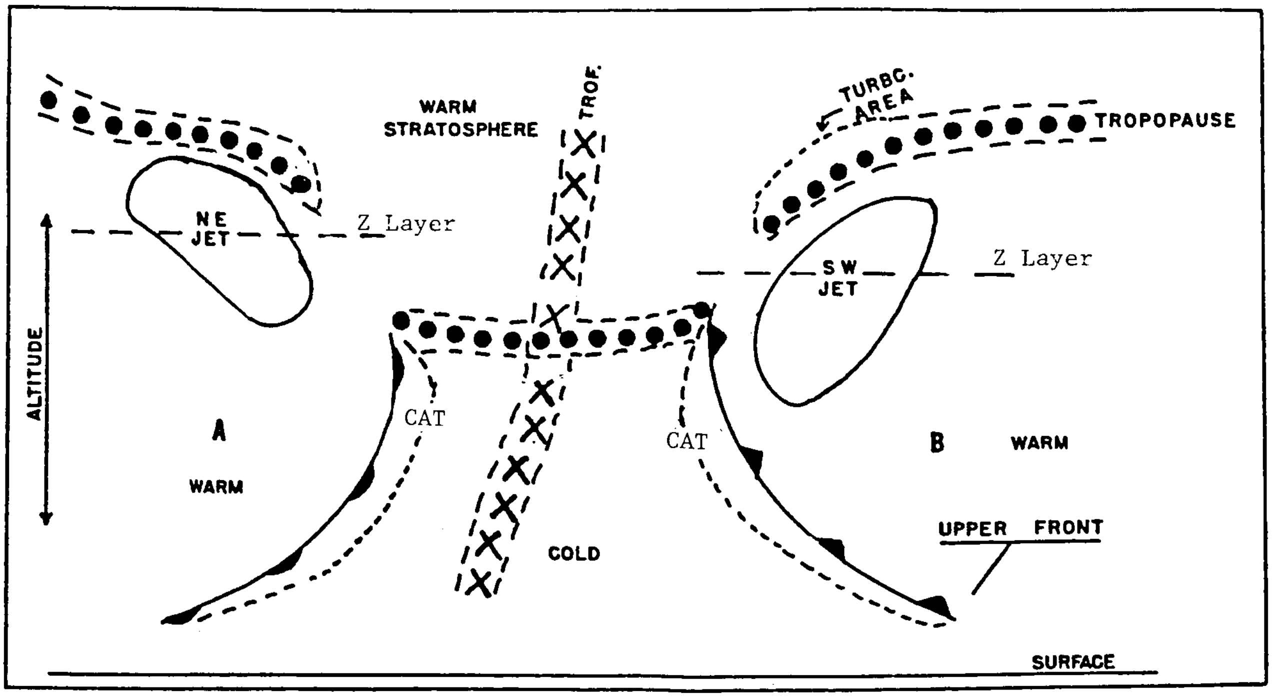


Figure 19. A vertical cross section along line AB which shows the areas of turbulence.

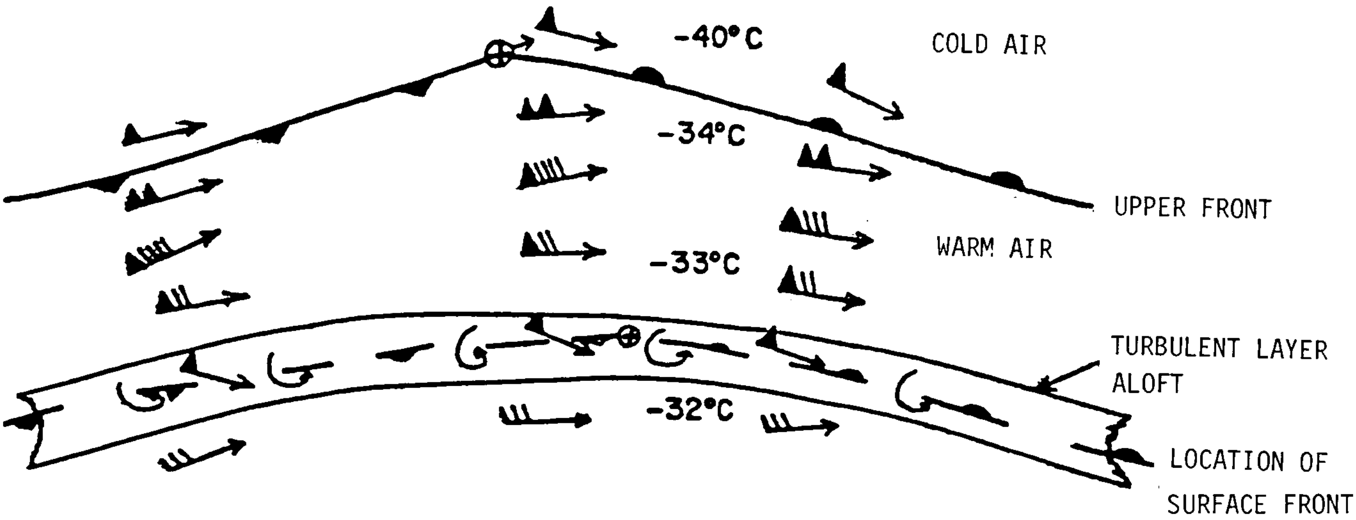


Figure 20. The position of the surface front and associated upper air position.

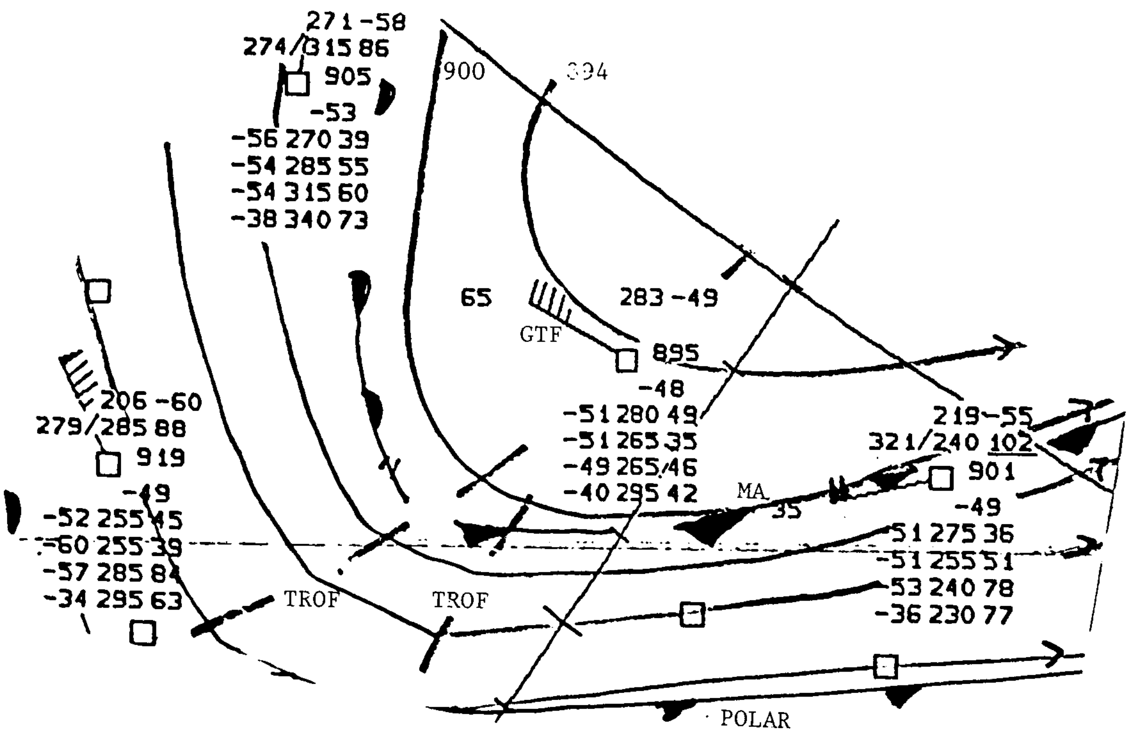


Figure 21. The actual for 1200Z on March 31, 1986, for the Pacific Northwest with maritime and polar fronts.

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GBTA0000/29-0600/29B20/1552/1546/1545/1541/1544/1540/1187/1183/
1186/1182/1185/1181/1184/1180#

AT 29/0000Z AN UPPER FRNT AT FL320 EXTENDS FRM BIS SUX OMA
MCI TUL TO DFW.SLOPING DOWN TO THE EAST..THE TROP AT FL360
ABV THE FRNT SLOPES UP TO THE EAST....BY 29/0600Z THE FRNT AND
TROP WILL BE ALONG A LINE FAR RWF IRK SOW LIT TXK GGG CLL.

LOOK FOR MOSTLY MDT TURBC THRU THE FRONTAL SLOPE FL180 UP TO
FL260 AND LGT PSBL BRF MDT FL260 TO FL320..OCNL LGT TURBC THRU
THE SLOPE OF THE TROP.

FL330 AND FL350 THE Z LAYER SMOOTHEST WAY THRU..

A/C WEST BOUND BLO FL330 DESCEND AND ABV FL350 CLB FOR THE
FASTEST OUT....A/C EAST BOUND BLO FL330 CLB AND ABV FL350
DESCEND FOR FASTEST OUT..PATTON


GBTA0000/29-0600/29T21/1176/1181/1175/1180/1174/0823/0817#

AT 29/0000Z AN AREA OF SCTD TRW COVERS MOST OF MISS ALA THE
WESTERN FLA PANHANDLE AND WESTERN TENN..

A SCTD TO BRKN LINE OF TRW EXTENDS FRM MEM TO JAN AND MCB
TOPS IN THE LINE TO 400. THE CELLS ARE MOVING NE WHILE THE
LINE IS MOVING EAST. AND BY 29/03Z WILL EXTEND FRM 95SW BNA TO
MEI AND MSY TOPS NOW TO NEAR 470..BY 29/06Z THE LINE WILL EXTEND
FRM BNA TO BHM CKL MOB..TOPS NOW DOWN TO 410..LINE TO CONTINUE
EAST BEYOND FORECAST PERIOD.....PATTON
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Figure 22. A sample Delta Air Lines turbulence alert that is entered into the flight planning system.